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Impactor mass and source cutoff frequency estimations for three large impacts detected by the Apollo seismometers

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Let us consider the source excitation process for an impact where an impactor is instantaneously absorbed by the surface without ejecta generation. The associated seismic force can then be modeled as a point force, with a seismic force given by

$$F_0(t,\mathbf{x})=m\mathbf{v}\,\delta(t)\,\delta(\mathbf{x}-\mathbf{x}_s), \qquad (1)$$

*where m is the mass, **v** is the velocity vector (v being the velocity amplitude), δ is the Dirac's delta function, t and **x** are time and position variables. The acceleration spectrum of seismic waves generated by impacts is expected to grow as ω^3, whereas the acceleration spectrum of quakes only grows as ω^2. The examination of typical Apollo data however shows that this intuitive idea is far from observations. (see fig.1)*

Following [1], we assume a simple model for the seismic source function, namely, a time-dependent force acting downward on the surface of the planet during the impact, which takes into account the fact that part of the seismic force could be associated with ejecta material [2]. Let the time dependant seismic source function be in the form:

$$f(t,\mathbf{x}) = m\mathbf{v}\,\delta(x-x_s)\,g(t) = f(t)\,\delta(x-x_s) = F_0(t,\mathbf{x})*g(t), \qquad g(t)=1+\cos\omega_1 t \ \text{ for } -\pi/\omega_1<t<\pi/\omega_1,\ g(t)=0 \ \text{ otherwise}, \qquad (2)$$

*where g(t) is the time dependence of the source, * is a convolution product [3]. We introduce the time constant, τ, equal to $2\pi/\omega_1$ to denote the time-duration of the excitation process, as well as the seismic impulse, defined as an intergral of the equivalent force f(t). We define the seismic amplification parameter as S=I/mv. The Fourier transform of g(t) is proportional to ω^{-3} for angular frequencies higher than the cutoff angular frequency ω_1. That is why we expect the seismic acceleration spectrum, which varies as ω^3 at low frequency for an impact, to be flat after the cutoff frequency and even to decrease due to additional effects such as attenuation.*

The amplitude of the spectrum recorded at a given epicentral distance D can be approximated as $\hat{s}(\omega) = B\omega^3 \exp(-\frac{\omega t_{prop}}{2Q}) \times \hat{g}(\omega)$

where B is a constant depending on the seismic impulse and epicentral distance, Q the quality factor related to attenuation (Fig.2).

We determined by a least squares fit to the logarithmic amplitudes, the best values for Q, τ and B by a grid search. We get a very good fit to the data for seismic source function in the form (2), and an unrealistically low Q values and much lower variance reduction for (1).

Below 0.5 Hz, we recognize the ω^3 and ω^2 slopes, but see a clear weakening of the impact spectrum above about 1 Hz. As we will see, the differences in the spectrum are mainly due to source processes.

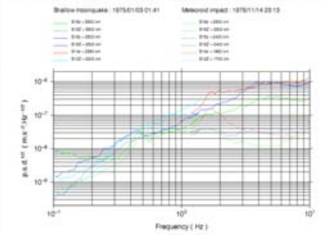

Fig. 1 : The comparison of typical spectra of impact signals (14 Nov 1976, lat. 23.80, long. -73.90) with those of quakes (3 Jan 1975, lat. 26.10, long. -92.70). The events are at comparable distances Z is long period and z is short period components, respectively. Solid and dashed lines indicate ω^2 and ω^3 slopes.

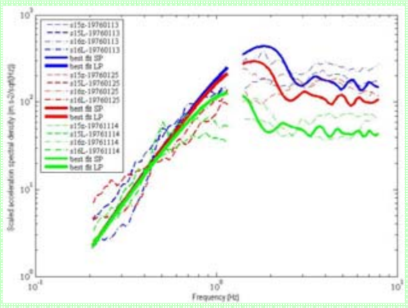

Fig. 2: Log-log plot of the scaled acceleration spectral density for three large meteoroids impacts, recorded on LP and SP vertical components at stations 15 and 16. The blue, red and green lines are the theoretical scaled acceleration spectral densities calculated for simulated events (13 January, 25 January and 14 November 1976, τ=0.7, 0.8, 1.05 s, respectively) with the assumed source function in the form of (2). The dashed lines are least square fit of logarithmic amplitudes. In addition to the seismic impulse scaling, the attenuation effect has been correctedby multiplying the spectrum by $\exp(\omega t_{prop}/2Q)$, where Q is the quality factor found by the least squares inversion.

For artificial impacts of the LM and SIVB Apollo upper stages the method allows us to retrieve the mass within 20% of relative error.

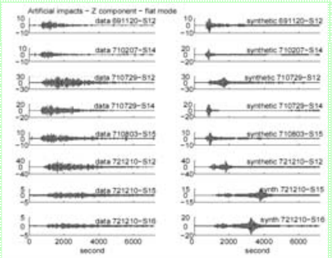

Fig. 3: Synthetic lunar seismograms (right) and data set recorded at the stations (left) for some man-made signals. The abscissa is the duration (s), the ordinate is the amplitude (in DUs). The date of the event and the name of the station recorded the event are given. The data set and synthetics are band-pass filtered, with a cosine taper with frequencies between 0.2 and 0.4 Hz.

Synthetic seismograms are computed for a spherical model of the Moon. They are unable to match the waveforms of the observations, but nevertheless provide an approximate measure of the energy of seismic waves in the coda. It allows us to compute a rough estimation of the seismic energy in a given time window. Its square root, equivalent to the mean rms in the window, is proportional to the seismic impulse, i.e. the time integrated seismic force.

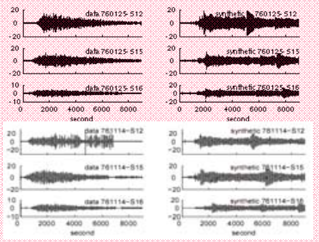

Fig.4:Synthetic lunar seismograms with momentum transfers listed in Table 1 compared with data set recorded at the stations (left) for the events: 25 January 1976 and 14 November 1976. See also caption to Fig.3.

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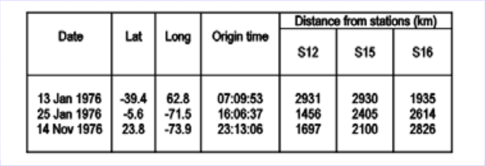
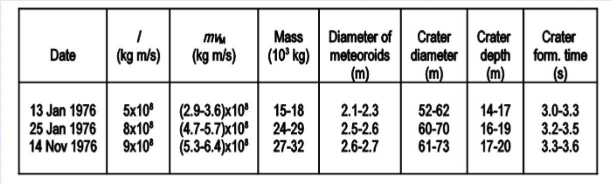
Table 1. Meteoroid impacts



Date	Lat	Long	Origin time	Distance from stations (km)		
				S12	S15	S16
13 Jan 1976	-39.4	62.8	07:09:53	2931	2930	1935
25 Jan 1976	-5.6	-71.5	16:06:37	1456	2405	2614
14 Nov 1976	23.8	-73.9	23:13:06	1697	2100	2826

Table 2. Estimated masses and diameters of meteoroids. The seismic amplification due to ejecta is in the range of 1.4-1.7, depending on the impact angle (for the density of 3000 kg/m³ by assuming a 20 km/s impact velocity).



Date	*I* (kg m/s)	mv_M (kg m/s)	Mass (10^3 kg)	Diameter of meteoroids (m)	Crater diameter (m)	Crater depth (m)	Crater form. time (s)
13 Jan 1976	5×10^8	$(2.9\text{-}3.6)\times10^8$	15-18	2.1-2.3	52-62	14-17	3.0-3.3
25 Jan 1976	8×10^8	$(4.7\text{-}5.7)\times10^8$	24-29	2.5-2.6	60-70	16-19	3.2-3.5
14 Nov 1976	9×10^8	$(5.3\text{-}6.4)\times10^8$	27-32	2.6-2.7	61-73	17-20	3.3-3.6

Conclusion

We have estimated the impulse response and frequency properties of some largest meteoroid impacts and determined the possibility to use, in the future, such impacts to study the thickness and structure of the lunar crust. We show that their masses can be estimated with rather simple modeling technique and that high frequency seismic signals have reduced amplitudes due to a relatively low (about 1sec) corner frequency resulting from the duration of the impact process and the crater formation.

Current estimates of the size of the meteoroids (diameter of 2-3 meters) indicate that they could create craters of about 50-70 meters in diameter: it might therefore be possible for the future NASA Lunar Reconnaissance Orbiter mission to detect these craters. Future seismometers must have performances at least 10 times better than Apollo in order to get these surface waves from comparable impacts. Such a resolution will also allow the detection of several impacts of low mass (1-10 kg) at a few 10s to hundred km of each station, which might be used to perform local studies of the crust.

References :

[1] McGarr et al., 1969. J.Geophys.Res. 74, N 25, 5981-5994, doi :10.1029/JB074i025p05981.
[2] Lognonné et al., 2009. J. Geophys. Res., 114, E12003,, doi:10.1029/2008JE003294
[3] Gudkova et al., 2010. Icarus. in press.